AD-A110 576 ROYAL SIGNALS AND RADAR ESTABLISHMENT MALVERN (ENGLAND) F/G 17/2
AN ANNOTATED BIBLIOGRAPHY OF CONGESTION CONTROL IN PACKET-SWITC--ETC(U)
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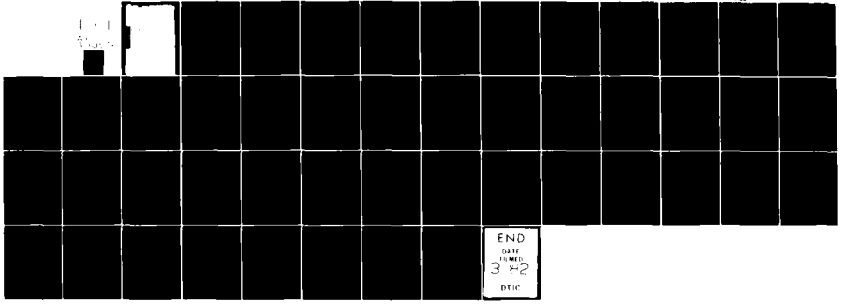

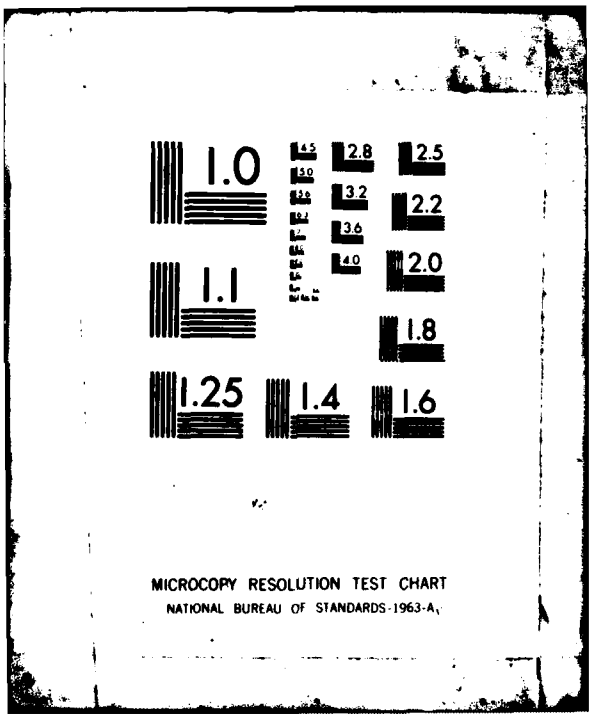
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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Report No 81011

Title: AN ANNOTATED BIBLIOGRAPHY OF CONGESTION CONTROL IN PACKET-SWITCHED COMMUNICATIONS NETWORKS

Author: D P Taylor

Date: November 1981

SUMMARY

The control of congestion in packet-switched networks is a topic which has attracted considerable interest particularly over the past few years when it has been recognised that effective congestion control is an essential feature of network design if reliable communications are to be maintained under adverse conditions, such as traffic overloading, failure situations and in damage. However, because congestion control necessarily embraces all other network control mechanisms, such as routing, flow control, deadlock prevention and buffer assignment strategies, the complex resultant control problem is difficult to analyse and is indeed still an active area of research. This paper provides an annotated bibliography of some of the more important publications in the open literature which deal with pertinent aspects of congestion control.

RSRE REPORT NO 81011

AN ANNOTATED BIBLIOGRAPHY OF CONGESTION CONTROL IN PACKET-SWITCHED COMMUNICATIONS NETWORKS

D P Taylor

LIST OF CONTENTS

1 INTRODUCTION

The control of congestion in packet-switched networks is a topic which has attracted considerable attention over the past few years when it has been recognised that effective congestion control is an essential feature of network design if reliable communications are to be maintained under adverse conditions such as traffic overloading, failure conditions and in damage. Indeed, it is noteworthy that a special issue of the IEEE Transactions on Communications on congestion control was published in April 1981.

This annotated bibliography identifies some of the important publications which relate to congestion control and, in addition, provides brief observations on each of the publications identified. The motivation for the production of this annotated bibliography stems from the desire within RSRE to perform fundamental intra and extramural research into congestion control, particularly with military networks in mind which must be reliable under all conceivable adverse conditions and for which congestion, leading to network deadlock, would be tantamount to disaster.

Figure 1 gives an indication of the many network mechanisms which, when acting in a homogeneous manner can be described under the broad heading of "Congestion Control". The main aspects of congestion control are: routing, flow control, deadlock prevention, topological considerations and buffer assignment strategies. Perhaps one way of conceiving congestion control is as a classic feedback and control problem. This analogy, which should not be extended too far without considerable thought, is useful in that if we

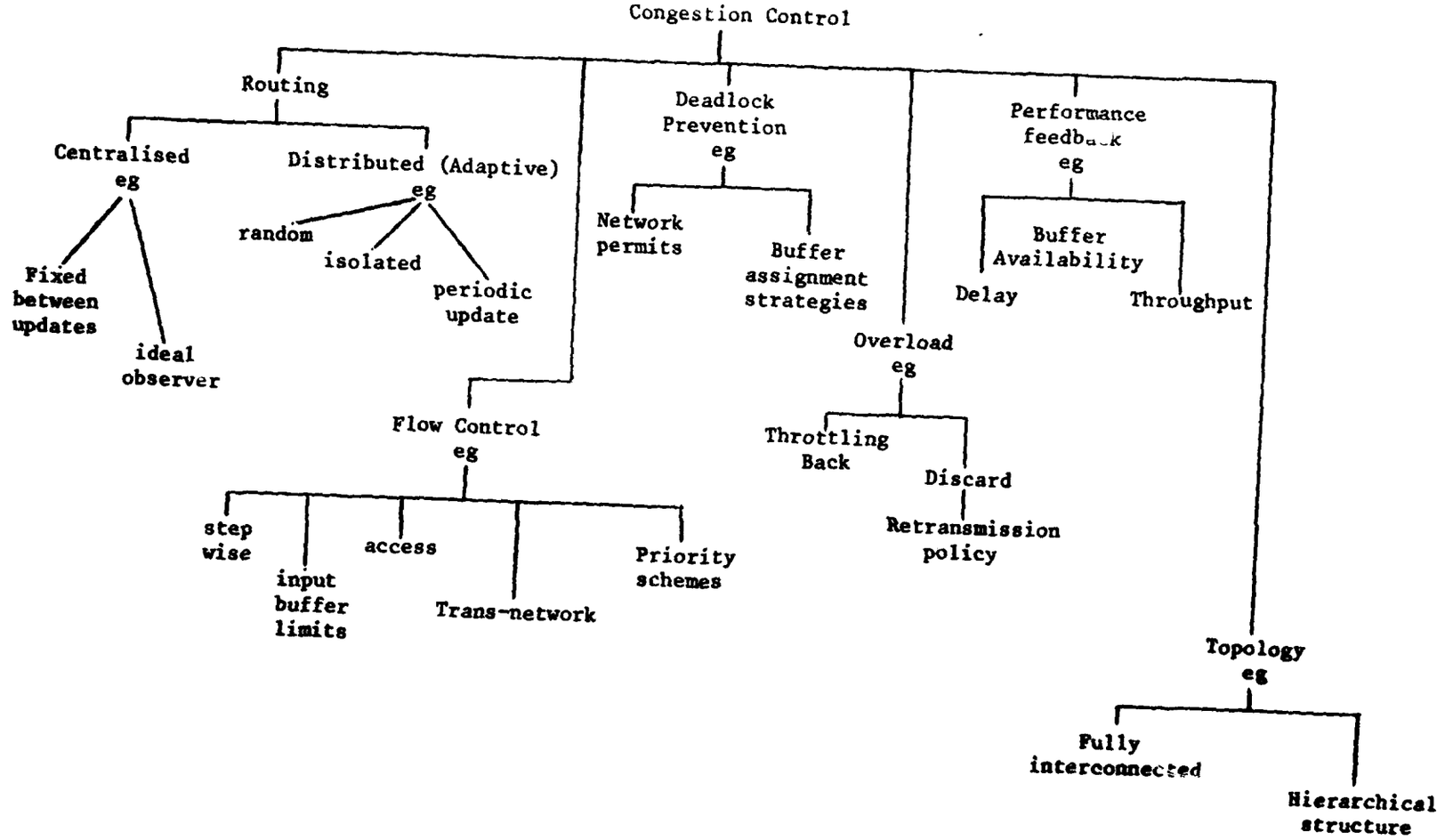
Congestion Control
Routing
Centralised
eg
Fixed
between
updates
ideal
observer
Distributed (Adaptive)
eg
random
isolated
periodic
update
Deadlock
Prevention
eg
Network
permits
Buffer
assignment
strategies
Performance
feedback
eg
Buffer
Availability
Delay
Throughput
Overload
eg
Throttling
Back
Discard
Retransmission
policy
Flow Control
eg
step
wise
input
buffer
limits
access
Trans-network
Priority
schemes
Topology
eg
Fully
interconnected
Hierarchical
structure

FIGURE 1

consider a packet-switched network as a data reservoir, which it is by virtue of packet queueing, then the potential problems associated with phenomena such as hysteresis and oscillations can be readily appreciated. In addition the feedback data perhaps generated by nodal periodic updates will be out of date and possibly incorrect by the time it reaches the point of control. Therefore, congestion control is a complex, multi-variable dynamic problem which, as a total study, is not amenable to currently available analytic solutions or indeed to manageably-sized simulators. Furthermore, each individual aspect of congestion control, for example routing, presents in its own right considerable analysis problems. Because of these analysis problems, the comparison between the results of different workers in the field is often difficult and this leads to many opinions on the merits of any one particular scheme. However, it is true to say that there is agreement in certain areas. For example, there is general agreement that the congestion control of large, ie greater than 50 node networks, is still an active area of research. This is particularly true for damage scenarios in those networks having a distributed control structure. This aspect of distributed control is particularly important in the military environment where the use of a single network control centre, albeit with local back-up, is not in line with the requirement for survivability.

One definition of congestion control is the sharing of network resources to meet user demands and the restruction of user demands to a level which can be effectively handled by the network. If this control action is not taken in a timely manner then the traffic carrying capacity of the network will fall as will the quality of service provided to the users, both in terms of decreased throughput and increased delay. This degradation, in terms of throughput, is shown in figure 2. Ideally the transfer curve should not be permitted to pass into the negative slope region. However it is to be recognised that, particularly in the military environment, when damage occurs instantaneous local congestion will result and the control techniques must prevent the congestion from spreading in the first instance and then rapidly restrict user demands to a level which can be handled by the damaged network.

This annotated bibliography treats each publication in an objective way, but does not attempt to reach any overall independent conclusion as to the merits of individual congestion control strategies. It is planned that the analysis of congestion control in military packet-switched networks will be covered in a future paper.

2 THE ANNOTATED BIBLIOGRAPHY

Publications identified in this bibliography are grouped under the following headings:

i. Congestion Control

Publications which attempt to deal with the total study, of congestion control.

ii. Flow Control, Buffer Allocation, Deadlock Prevention, Traffic Flow and Topological Considerations

Publications which deal with one or more of these three aspects.

iii. Routing

Publications which have an emphasis on routing.

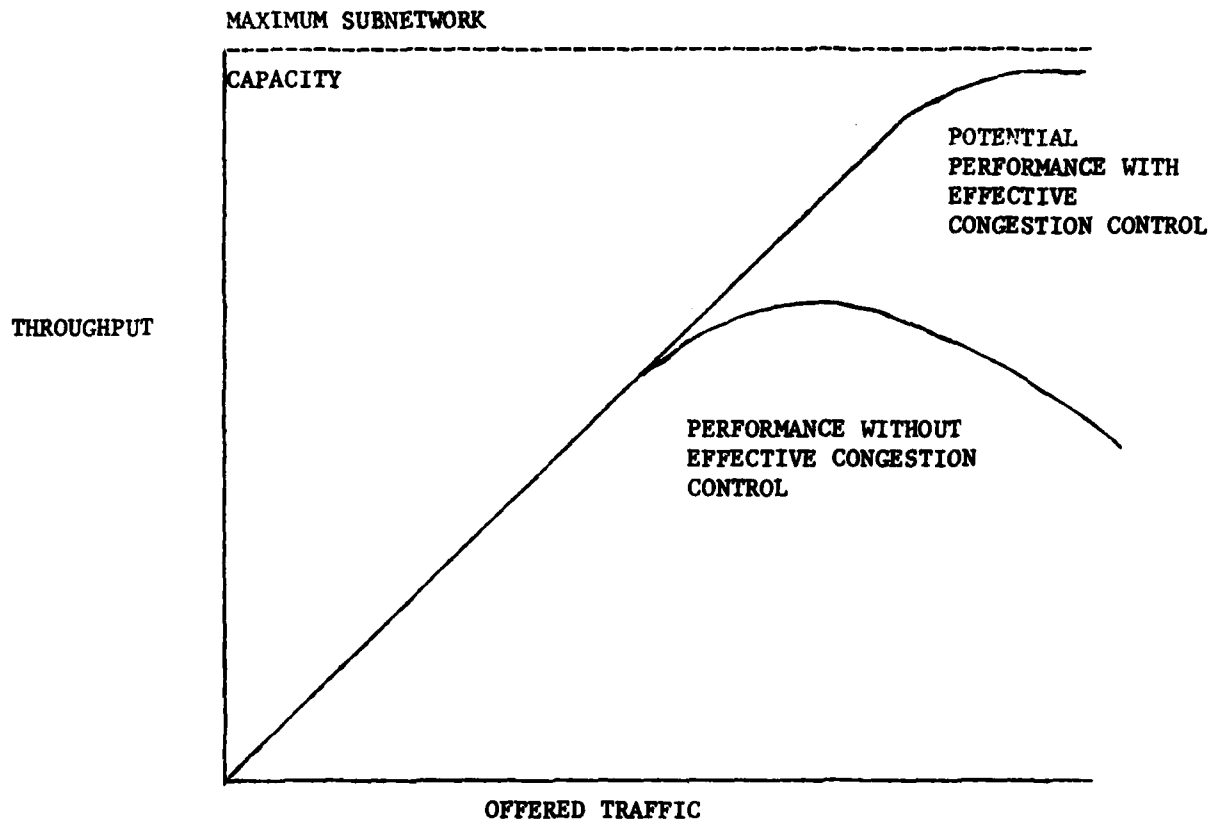
MAXIMUM SUBNETWORK
CAPACITY
POTENTIAL
PERFORMANCE WITH
EFFECTIVE
CONGESTION CONTROL
THROUGHPUT
PERFORMANCE WITHOUT
EFFECTIVE CONGESTION
CONTROL
OFFERED TRAFFIC

FIGURE 2

It must be appreciated that a considerable overlap of interest occurs in some of the publications which makes precise categorisation difficult. One note of caution is that the terminology used in the publications identified is not always consistent particularly as the bibliography spans a 17 year period. However, as far as possible common terminology has been used in the notes for each publication.

Appendix A provides a list of all those publications which were reviewed in the preparation of this annotated bibliography.

2.1 CONGESTION CONTROL

Twenty-two publications are detailed in this section, each one of which attempts to look at the wider issues of congestion control in that they take the view that congestion control embodies more than one isolated aspect of network design. For example the effect of adaptive routing cannot be divorced from flow control considerations.

2.1.1 Section list of publications

ANALYSIS OF A PACKET-SWITCHED NETWORK WITH END-TO-END CONGESTION CONTROL AND RANDOM ROUTING. A Chatterjee, N Georganas and P Verma. 1976.

A UNIFIED FLOW AND CONGESTION CONTROL MODEL FOR PACKET-NETWORKS. W Chou and M Gerla. 1976.

COMPUTER NETWORKS AND THEIR PROTOCOLS. D Davies, D Barber, W Price and C Solomonides. 1979.

ANALYSIS OF PACKET NETWORK CONGESTION CONTROL USING SPARSE MATRIX ALGORITHMS. L Kaufman, B Gopinath, E Wunderlich. 1981.

A SIMULATION STUDY OF ROUTING AND FLOW CONTROL PROBLEMS IN HIERARCHICALLY CONNECTED PACKET-SWITCHING NETWORK. I Kerr, G Gomberg, W Price and C Solomonides. 1976.

QUEUEING SYSTEMS VOLUME 2 COMPUTER APPLICATIONS. L Kleinrock. 1976.

FLOW CONTROL IN SWITCHED TELEPHONE NETWORKS: THEORY AND EXPERIENCE EXTENSION OF THEORY TO PACKET-SWITCHED NETWORKS. C Lemieux. 1979.

THEORY OF FLOW CONTROL IN SHARED NETWORKS AND ITS APPLICATION IN THE CANADIAN TELEPHONE NETWORK. C Lemieux. 1981.

FLOW AND CONGESTION CONTROL IN SL-10 NETWORKS. F Magoon and D Twyver. 1979.

EXPERIMENTS IN CONGESTION CONTROL TECHNIQUE. J Majithia, M Irland, J Grange, N Cohen and C O'Donnell. 1979.

DESIGNING RELIABLE PACKET-SWITCH COMMUNICATION NETWORKS. K Maruyama. 1978.

FLOW CONTROL IN PACKET-SWITCHED NETWORKS BY GRADUAL RESTRICTIONS OF VIRTUAL CALLS. J Matsumoto, H Mori. 1981.

QUALITATIVE ANALYSIS OF CONGESTION SENSITIVE ROUTING. W Older. 1979.

THE INFLUENCE OF CONTROL PROCEDURES ON THE PERFORMANCE OF PACKET-SWITCHED NETWORKS. H Opderbeck and L Kleinrock. 1974.

CONGESTION CONTROL IN THE STORE AND FORWARD TANDEM LINKS. M Pennotti and M Schwartz.

METHODS, TOOLS AND OBSERVATIONS ON FLOW CONTROL IN PACKET-SWITCHED DATA NETWORKS. L Pouzin. 1981.

NETWORK MANAGEMENT RESEARCH. C V Ramamoorthy. 1980.

CHAIRMAN'S REMARKS AND INTRODUCTION TO FLOW CONTROL. H Rudin. 1976.

DYNAMIC ROUTING AND FLOW CONTROL. H Rudin and H Mueller. 1980.

COMPUTER COMMUNICATION NETWORK DESIGN AND ANALYSIS. M Schwartz. 1977.

ROUTING FLOW AND CONGESTION CONTROL IN THE DATAPAC NETWORK. D Sprole and F Mellor. 1981.

COMPUTER NETWORKS. A S Tanenbaum. 1981.

ANALYSIS OF A PACKET-SWITCHED NETWORK WITH END-TO-END CONGESTION CONTROL AND RANDOM ROUTING
A Chatterjee, N Georganas and P Verma
Proceedings International Conference on Computer Communications (Toronto) 1976

This paper makes the point that the performance of end-to-end congestion control when used in conjunction with adaptive routing is not amenable to mathematical modelling for analysis. However, end-to-end congestion control and random routing can potentially be mathematically modelled under steady state conditions and the authors suggest that such an analysis may be indicative of the performance of adaptive routing with end-to-end congestion control. A queueing model is presented and techniques developed for its analysis with end-to-end congestion control and random routing under steady state conditions.

The results of the application of the queueing model to a specific three node network are given which demonstrates that the distribution of load by the use of random routing decreases average network congestion over fixed routing.

A UNIFIED FLOW AND CONGESTION CONTROL MODEL FOR PACKET-NETWORKS
W Chou and M Gerla
Proceedings International Conference on Computer Communications (Toronto) 1976

The view taken by the authors is that because experiments using a simplified simulation model are more straightforward and less expensive than measurements on an operating network, it is essential that a congestion control scheme be simulated before network implementation. However, this implies that traffic parameters are known at simulation time which may not always be the case, as other workers have shown that the choice of control scheme is influenced by the characteristics of the offered traffic.

This paper highlights that the interaction between the individual parameters of any one flow and congestion control strategy requires that if simulation is to be meaningful, then it must take into account all the parameters. For example, the parameters of a flow and control strategy may include the routing algorithm, end-to-end flow control, network access flow control and node to node flow control.

A functional description of the simulator is given and the results of comparing a virtual call orientated protocol based on ARPA and a datagram orientated protocol are given for fixed and adaptive routing. One of the findings of the simulated performance of adaptive routing in the virtual call environment was that adaptive routing only gave a marginal improvement in performance over fixed routing. However, to put this into context it is to be noted that link or node failures were not simulated.

COMPUTER NETWORKS AND THEIR PROTOCOLS
D Davies, D Barber, W Price and C Solomonides
Published by John Wiley 1979

This book which is particularly up-to-date, provides in Chapters 3 and 4, some general discussions and specific examples of congestion control in packet-switched communications networks and is recommended as providing a good introduction to the subject.

A distinction is drawn between flow control and congestion avoidance where flow control is concerned with the integrity of packet transmission and protection of network entities, such as destination nodes from overload. Congestion avoidance is interpreted as those mechanisms which protect the whole or part of the network from blockage due to an aggregation of excess traffic. Link and source to destination node flow control is described and examples are drawn from ARPA. The causes of congestion are identified and methods for congestion avoidance are outlined which includes isarithmic techniques first proposed by Davies.

ANALYSIS OF PACKET-NETWORK CONGESTION CONTROL USING SPARSE MATRIX ALGORITHMS
L Kaufman, B Gopinath, E Wunderlich
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

As more detail, such as window mechanisms, are added to a network queueing model, then the model often is no longer amenable to an analytic solution. This paper proposes a detailed queueing model which includes window mechanisms and node-to-node blocking, and then analyses the model using a numerical sparse matrix method. The paper provides information on sparse matrix techniques to enable other workers to make use of the method.

The following congestion strategies are analysed in the paper using the technique proposed:

1. Common buffer pool with packet discard on buffer full.

2. Differentiation between transit and local traffic. An approach which throttles back the source traffic to a level which can be guaranteed to be transmitted across the network.

Strategy 2 was found to be superior to strategy 1. One of the reasons for this superiority being that all packets accepted are processed and that excess traffic is restricted at source rather than being discarded after consuming network resources.

The conclusions of the paper are that the sparse matrix method is able to analyse more detailed models of packet-switched networks than can be handled via analytic methods. In addition, the use of a buffer reservation scheme as proposed in technique 2, can assist in the control of congestion in a packet-switched network.

A SIMULATION STUDY OF ROUTING AND FLOW CONTROL PROBLEMS IN HIERARCHICALLY CONNECTED PACKET-SWITCHING NETWORK
I Kerr, G Gomberg, W Price and C Solomonides
Proceedings International Conference on Computer Communications (Toronto) 1976

This paper describes the results of simulation of packet-switching in a hierarchically organised network. Two methods of routing, fixed and adaptive, are simulated. The adaptive routing algorithm is of the minimum hop type but with a bias favouring routes via the high level network. Two methods of flow control are simulated; isarithmic flow control and a method which depends on a fairly direct feed back from a congested link to the point of input to the network. The main conclusions of the paper are that:

1. The simple adaptive routing algorithm improved performance over a fixed routing algorithm.

2. Load splitting for simultaneous use of more than one path increases throughput.

3. Hierarchically organised networks posed particular congestion control problems, especially as far as network lock-ups are concerned.

QUEUEING SYSTEMS VOLUME 2 COMPUTER APPLICATIONS
L Kleinrock
Published by Wiley Inter-Science (1976)

This book, together with Volume 1 of Queueing Systems, is a standard work on the application of queueing theory to computer networks. In addition to providing a detailed description of queueing theory and its use in computer networks design and analysis, Chapter 6 of this book describes aspects of congestion control and gives a useful summary of some of the experiences with ARPANET.

FLOW CONTROL IN SWITCHED TELEPHONE NETWORKS: THEORY AND EXPERIENCE EXTENSION OF THEORY TO PACKET-SWITCHED NETWORKS
C Lemieux
Flow Control in Computer Networks, IFIP North Holland Publishing Company (1979)

This discussion paper provides some interesting comparisons between flow control in circuit-switched networks and its extension to packet-switched networks. Various methods of flow and congestion control for packet-switched networks are discussed. The problem of discarded packets under conditions of network congestion which lead to an increase in congestion by virtue of retransmissions is discussed, as is the effect of the choice of node buffer sizes and window sizes. One of the general conclusions of the paper is that complete flow and congestion control strategies must always be implemented.

THEORY OF FLOW CONTROL IN SHARED NETWORKS AND ITS APPLICATION IN THE CANADIAN TELEPHONE NETWORK
C Lemieux
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

This paper is an extended version of Lemieux' paper "Flow Control in Switched Telephone Networks: Theory and Experience. Extension of Theory to Packet-Switched Networks". This paper provides a qualitative analysis of congestion control in circuit and packet-switched networks and provides a variety of network transfer curves and a number of useful comparisons are drawn between circuit switching and packet switching in terms of flow control and congestion avoidance.

FLOW AND CONGESTION CONTROL IN SL-10 NETWORKS
R Magoon and D Twyver
Flow Control in Computer Networks. IFIP, North Holland Publishing Company (1979)

This paper, the result of theoretical work and practical experience, describes flow and congestion control mechanisms in SL-10 networks of which DATAPAC is an example. The paper is particularly interesting as it describes the network which offers an X25 virtual call service supported by datagram sub-network, a design of current military interest.

Separate window mechanisms are used for access and trans-network working and the differentiation between transit and new traffic is utilised such that in congestion new traffic is discarded while transit traffic is, if possible, unaffected. The discard of new traffic leads to three repeat re-transmissions following which a call is cleared with the cause "network congestion".

The problems associated with periodic routing update information being delayed under conditions of congestion is tackled by giving such routing information a special priority.

EXPERIMENTS IN CONGESTION CONTROL TECHNIQUES
J Majithia, M Irland, J Grange, N Cohen and C O'Donnell
Flow Control in Computer Networks, IFIP, North Holland Publishing Company (1979)

The authors take the view that flow and congestion control strategies should be directly related to the status of the network by which is meant that parameters such as link, utilisation and buffer occupancy should dynamically influence the flow and congestion control strategy. The use of window mechanisms such as X25 which only take an indirect account of network congestion are not in themselves suitable for the provision of total network congestion control.

The CIGALE network employs a datagram switching sub-network in which routing is adaptive. The network congestion control strategy proposed and simulated for CIGALE is based on the following:

1. An estimation of the network state performed on an adaptive basis in which link load is used as the basic measurement of congestion.

2. The propagation of congestion information to the access nodes.

3. The propagation of congestion information to the hosts.

The basic algorithm proposed is that, based on congestion information received, each host can selectively throttle back traffic on a per destination basis. In addition, a fall-back mechanism is implemented whereby in the event of hosts ignoring congestion warnings or inadequate host reaction, then traffic on a per destination basis is discarded by the access nodes.

One of the conclusions of the paper is that the congestion control mechanisms proposed tend to reduce network throughput at low loads. However, their reaction to the onset of congestion is effective and it is suggested that with some fine tuning, the effect of reducing network throughput at low load could be lessened.

DESIGNING RELIABLE PACKET-SWITCH COMMUNICATION NETWORKS
K Maruyama
Evolutions in Computer Communications. Proc. ICCC Kyoto September 1978

This paper addresses the point that network design should not only concern itself with the optimisation of network performance, but should also consider the network reliability under node and link failures. However, due to the complexity of the resultant design problem, no exact solution is available.

One possible design algorithm is outlined and approximation methods are identified.

FLOW CONTROL IN PACKET-SWITCHED NETWORKS BY GRADUAL RESTRICTIONS OF VIRTUAL CALLS
J Matsumoto, H Mori
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

This paper deals with congestion control in virtual call access networks and in particular deals with international packet-switched networks based on CCITT X75. The authors' view is that previous studies on flow control have not considered the aspects of establishment of virtual calls prior to the passage of data.

The paper proposes a flow control technique in which packet queue lengths to individual outgoing routes are constantly observed and that packet flows through virtual calls connected to a congested outgoing route are gradually restricted depending on queue lengths. A simple queueing model is derived to analyse the effect of gradual restriction of throughput of virtual calls and the method, when compared with no other controls, is shown to be effective.

QUALITATIVE ANALYSIS OF CONGESTION SENSITIVE ROUTING
W Older
Flow Control in Computer Networks. IFIP North Holland Publishing Company (1979)

Packet-switched networks which are to provide a service under damage and failure conditions must incorporate feed back. The author's view is that these non-linear feed-back loops are difficult to analyse, with manifestations such as hysteresis and bistability being difficult to eliminate.

The author suggests that simulation of packet-switched networks to quantify the effects of feed-back is difficult, some of the problems being associated with assessing which information is relevant and which

is not, and although analytic models are very much simpler than simulations they share many of the same problems.

A qualitative approach to the analysis of packet-switched networks is proposed as an alternative technique and a description of the approach is given.

THE INFLUENCE OF CONTROL PROCEDURES ON THE PERFORMANCE OF PACKET-SWITCHED NETWORKS
H Opderbeck and L Kleinrock
Proceedings National Telecommunications Congress December 1974

This paper draws on the experiences of the ARPANET catastrophic failures, the deadlocks and less catastrophic failures shown up as network degradation which had been proved to have been caused by faults in the network flow control procedure. The reasons why optimisation of network performance is difficult when a network is responsible for carrying different traffic types is described and flow control principles are described under the local and global heading in addition a description of ARPANET lock-ups and throughput degradations are outlined.

The authors conclude that the design of flow control procedures is fraught with hidden dangers and that even "obviously" correct procedures may lead to catastrophic failures. The authors propose that one solution is to use a very simple flow control procedure which can be certified as safe. One other possible solution is the use of formal protocol proving techniques, but this can lead to an enormous test problem.

CONGESTION CONTROL IN THE STORE AND FORWARD TANDEM LINKS
M Pennotti and M Schwartz
IEEE Transactions on Communications Vol Com 23 No 12 December 1975

A queueing model for the analysis of congestion control is derived for a tandem link network. However the authors conclude that because the analysis of the model is not tractible, simulation may be required.

METHODS, TOOLS AND OBSERVATIONS ON FLOW CONTROL IN PACKET-SWITCHED DATA NETWORKS
1 Pouzin
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

This paper is an extended version of Pouzin's earlier paper "Flow Control in Data Networks, Methods and Tools". This paper covers new ground particularly in the memory-less applications, eg Ethernet and Aloha. The paper provides a useful overview of congestion control and gives a description of many of the methods proposed in the literature and examples of approaches taken by specific networks such as Tymnet, Transpac, GMD net, ARPANET, and Datapac are given.

The main conclusions of the paper are that congestion control in packet-switched networks is still an active research area and that obstacles to comprehensive theoretical understanding of congestion control are the number of parameters involved and the transient nature of congestion control. In addition, distributed as opposed to centrally controlled networks provide special problems in that if instability is to be avoided, all nodes must have available consistent information. However, as the updating process takes a finite time, there will be a "blind" state during which a new global view is being phased in.

NETWORK MANAGEMENT RESEARCH
C V Ramamoorthy
US Army Research Office. AD-A092055 (1980)

This is an interesting paper which tackles various problems relating to the control of large tactical distributed data networks. Areas of particular interest on which this paper concentrates are:

> Routing Control in which a fast shortest path adaptive routing algorithm is described.
>
> Reconfiguration Control, where four different models of dynamic reconfigurable systems are investigated and a reconfiguration procedure is developed using Petri-net models,

and Deadlock detection in which distributed deadlock detection is discussed and an algorithm outlined.

CHAIRMAN'S REMARKS AND INTRODUCTION TO FLOW CONTROL
H Rudin
Proceedings International Conference on Computer Communications (Toronto) 1976

A useful overview paper which identifies the need for flow and congestion control.

DYNAMIC ROUTING AND FLOW CONTROL
H Rudin and H Mueller
IEEE Transactions on Communications Vol Com 28 No 7 July 1980

This paper addresses the problem of flow and congestion control in networks employing adaptive routing. A simple analytic model is derived which is used to show that adaptive routing reduces the performance of a network at high network loading.

Simulation work is then described for a 10 node network. The work was performed to determine the performance and the effect of differing routing algorithms for:

1. Network without end to end flow control.
2. Network with end to end flow control.
3. The effect of modifying the routing algorithm up-date interval.
4. Effect of increase in number of alternative paths.

The general results of the simulation were that adaptive routing, although providing advantages at moderate loads, should be inhibited at high loads to prevent network performance degradation.

COMPUTER COMMUNICATION NETWORK DESIGN AND ANALYSIS
M Schwartz
Published by Prentice Hall 1977

This book provides a very digestible account of the issues in the design and analysis of computer networks. Many examples of practical network experience and previously published papers in the open literature being given. Chapter 11 provides a useful introduction to congestion control in computer communication networks.

ROUTING FLOW AND CONGESTION CONTROL IN THE DATAPAC NETWORK
D Sprole and F Mellor
IEEE Transactions on Communications. Vol Com 29 No 4 April 1981

This paper provides an overview of congestion control in the DATAPAC network. DATAPAC provides an X25 virtual call service which is supported by a datagram switching sub-network which employs an adaptive routing based on a minimum hop and link capacity algorithm. Flow control is achieved by the use of co-operating window mechanism both for virtual call access and sub-network access. Sub-network congestion, which cannot be relieved by, for example, re-routing results in packets being discarded in the sub-network. Under discard situations retransmissions take place on time-out and to prevent retransmitted traffic from leading to network failure virtual calls are cleared following three consecutive attempts to retransmit.

COMPUTER NETWORKS
A S Tanenbaum
Prentice-Hall, Inc. 1981

This is one of the most recent books to be published on computer networks and while, by necessity, covering much well tread ground it brings the issues together in a manageable volume.

The difference between this and earlier books on the subject is the emphasis on protocols and in particular the ISO seven layer model. However as far as congestion control per se is concerned there is a useful, but brief section devoted to an overview of the subject.

2.2 FLOW CONTROL, BUFFER ALLOCATION, DEADLOCK PREVENTION, TRAFFIC FLOW AND TOPOLOGICAL CONSIDERATIONS

Twenty-six publications are detailed in this section, each one of which tends to concentrate on either flow control, buffer allocation, deadlock prevention, traffic flow or topological considerations. All of which are important aspects of congestion control.

2.2.1 Section list of papers

FLOW CONTROL IN THE PACKET-SWITCHING NETWORKS. B Belsnes. 1975.

OPTIMUM END-TO-END FLOW CONTROL IN NETWORKS. K Bharath-Kumar. 1980.

A NEW APPROACH TO PERFORMANCE ORIENTATED FLOW CONTROL. K Bharath-Kumar and J Jaffe. 1981.

THE CONTROL OF CONGESTION IN PACKET-SWITCHING NETWORKS. D Davies. 1972.

TOPOLOGICAL OPTIMISATION OF COMPUTER NETWORKS. H Frank and W Chou. 1972.

ANALYSIS AND DESIGN OF SURVIVABLE NETWORKS. J Frank and I Frisch. 1970.

ALGORITHMS FOR THE ANALYSIS OF COMPUTER COMMUNICATION NETWORKS WITH WINDOW FLOW CONTROL. N Georganas. 1980.

FLOW CONTROL STRATEGIES IN PACKET-SWITCHED COMPUTER NETWORKS. M Gerla and W Chou. 1974.

FREE BUFFER ALLOCATION: AN INVESTIGATION BY SIMULATION. A Giessler, J Hanle, A Konig and E Pade. 1978.

FLOW CONTROL BASED ON BUFFER CLASSES. A Giessler, A Jagemann, E Maser and J Hanle. 1981.

PREVENTION OF DEADLOCKS IN PACKET-SWITCHED DATA TRANSPORT SYSTEMS. K Gunther. 1981.

BUFFER MANAGEMENT IN A PACKET-SWITCH. M Irland. 1978.

A DROP AND THROTTLE FLOW CONTROL POLICY FOR COMPUTER NETWORKS. F Kamoun. 1981.

ARPANET LESSONS. L Kleinrock. 1976.

A STUDY OF FLOWS IN AN X25 ENVIRONMENT. J Labetoulle, G Pujolle and N Makou. 1979.

STORE AND FORWARD BUFFER REQUIREMENTS IN A PACKET-SWITCHING NETWORK. S Lam. 1976.

CONGESTION CONTROL OF STORE AND FORWARD NETWORKS BY INPUT BUFFER LIMITS. S Lam, M Reiser. 1977.

THE RSRE PILOT PACKET-SWITCHED NETWORK. P Masterman. 1980.

TRAFFIC MEASUREMENTS IN DATA NETWORKS, RECENT MEASUREMENT RESULTS AND SOME IMPLICATIONS. P Pawlita. 1981.

FLOW CONTROL IN DATA NETWORKS METHODS AND TOOLS. L Poujin. 1976.

A REVIEW OF THE FLOW CONTROL ASPECTS OF NETWORK SIMULATION STUDIES AT THE NATIONAL PHYSICAL LABORATORY. W Price. 1979.

METHOD OF DEADLOCK-FREE RESOURCE ALLOCATION AND FLOW CONTROL IN PACKET NETWORKS. E Raubold and J Haenle. 1976.

BUFFER SHARING IN COMPUTER COMMUNICATION NETWORK NODES. M Rich and M Schwartz. 1977.

ANALYSIS OF CONGESTION CONTROL TECHNIQUES IN COMPUTER COMMUNICATION NETWORKS. S Saad and M Schwartz. 1979.

INPUT BUFFER LIMITING MECHANISMS FOR CONGESTION CONTROL. S Saad and M Schwartz. 1980.

ANALYSIS OF FLOW CONTROL IN SWITCHED DATA NETWORKS. J Wong and M Unsoy. 1977.

FLOW CONTROL IN THE PACKET-SWITCHING NETWORKS
B Belsnes
Eurocomp on Communications Networks. On-Line (1975)

This paper takes an intuitive view of the role of end-to-end window mechanisms in avoiding network congestion and suggests that the window sizes are best determined for each virtual call by the source host. This view is based primarily on the assumption that at any instant the network state is closely related to its capacity and the round trip delay which can be estimated by each source host and the window can therefore be dynamically varied. It is to be noted that this approach is not amenable to X25 as level 3 does not allow window sizes to change during the progress of a virtual call.

OPTIMUM END-TO-END FLOW CONTROL IN NETWORKS
K Bharath-Kumar
IEEE International Conference Proceedings on Communications 1980

A tandem queueing model is described and used to demonstrate that optimum values for the rate at which packet are allowed to enter a message path, and the average total number of messages in the system, the average window size, can be derived. The network performance parameter selected for optimisation is that of power, ie the ratio of throughput to delay.

The author emphasises that the choice of window size is important for power optimisation and that flow control is more effective if dynamic window schemes are employed. He shows that the optimum window size for a throughput equal to half the link rate, with equal capacity links, is shown to be equal to the number of hops.

A NEW APPROACH TO PERFORMANCE ORIENTATED FLOW CONTROL
K Bharath-Kumar and J Jaffe
IEEE Transactions on Communications, Vol Com 29 No 4 April 1981

This paper addresses the performance of packet-switched networks which employ a centrally controlled virtual channel sub-network. The performance parameter, known as 'power', ie the ratio of throughput to delay, is used in the examination of a class of congestion control algorithms. The authors conclude that the performance measure power is difficult to optimise, and its desirability as a global parameter in a large network is unclear.

The concentration on virtual channel sub-networks makes this paper possibly more suited to civil, rather than military, networks.

THE CONTROL OF CONGESTION IN PACKET-SWITCHING NETWORKS
D Davies
IEEE Transactions on Communications Vol Com 20 No 3 June 1972

This is a widely referenced paper which introduces the idea of isarithmic network congestion control in which a finite number of packet carriers when empty, move randomly through the network. For a source to send a packet, it must first seize an empty packet carrier.

Much interest is expressed in the open literature on this idea, although in practice simulation work performed has demonstrated that there are difficulties in estimating the optimum number of packet carriers. This would be particularly true in the military environment when damage is considered.

TOPOLOGICAL OPTIMISATION OF COMPUTER NETWORKS
H Frank and W Chou
Proceedings IEEE, Vol 60, No 11, November 1972

This paper presents models for queueing and reliability analysis based on network topology. One of the conclusions of the paper is that the topological design of networks with greater than 25 nodes, requires considerable analytic programming skill.

ANALYSIS AND DESIGN OF SURVIVABLE NETWORKS
J Frank and I Frisch
IEEE Transactions on Communication Technology Vol Com 18 No 5 October 1970

This paper addresses the problem of designing a network which can survive enemy attack or natural disaster. Attention is drawn to earlier work which focused on the mathematical formulation of physically meaningful survivability criteria and an overview of survivability and survivability criteria is given. A review of models and approaches taken in earlier work is given which include simulation and the use of directed graphs.

The main conclusions of the paper are that:

1. Considerably more work is required in the study of network survivability.

2. Heuristic approaches can be used to reduce the complex problem to manageable level.

3. Routing, not addressed in this paper, needs to be considered.

ALGORITHMS FOR THE ANALYSIS OF COMPUTER COMMUNICATION NETWORKS WITH WINDOW FLOW CONTROL
N Georganas
IEEE International Conference Proceedings on Communications 1980

The author provides a brief but useful summary of algorithms for the analysis of flow control mechanisms. Flow control being sub-divided under the headings of end-to-end, local and global.

The difficulty in the analysis of network flow control mechanisms in large networks is highlighted as is the fact that the modelling of

packet-switched networks leads to queueing at network models for which general solutions exist only in special cases.

The conclusions of the paper are that the current limitations in queueing theory lead to use of approximations and that the resultant heuristic algorithms appear to be promising for the analysis of large networks. Also, the use of simulation should be limited to the verification of analytic models.

FLOW CONTROL STRATEGIES IN PACKET-SWITCHED COMPUTER NETWORKS
M Gerla and W Chou
NTC Conference Proceedings San Diego 1974

The authors present the view that adaptive routing is not in itself effective in the prevention of congestion and that adequate control procedures must be used to regulate packet input rates.

A simple general model is presented for the classification and evaluation of different flow control strategies and existing strategies are reviewed in outline.

The authors conclude that considerable further research is required to enable the proper evaluation of different flow control strategies.

FREE BUFFER ALLOCATION: AN INVESTIGATION BY SIMULATION
A Giessler, J Hanle, A Konig and E Pade
North Holland Publishing Company Computer Networks Volume 2 1978

This is a widely referenced paper which discusses the topics of flow control and the prevention of network deadlock by the dynamic allocation of node buffers both for virtual channel switching sub-networks and datagram sub-networks.

The performance of a variety of network topologies are simulated and the results given in terms of applied load against, throughput, transit delay and power ie ratio of throughput and mean transit delay. The process of network performance degradation under congestion is explained, and the hysteresis involved in the recovery from congestion is identified as being one of the reasons for avoiding network congestion by imposing some form of input buffer limit. One of the conclusions of the paper is that virtual channel switching sub-networks are more amenable to control than datagram switching sub-networks.

FLOW CONTROL BASED ON BUFFER CLASSES
A Giessler, A Jagemann, E Maser and J Hanle
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

This paper in essence provides a shortened version of Giessler's et al's paper, "Free buffer allocation and investigation by simulation". Certain additional observations on congestion control in virtual circuit switching sub-nets by the use of node buffer classes are given.

The authors conclude that the buffer class concept proposed guarantees deadlock prevention and permits buffer control activity to be controlled locally thus giving a form of distributed network control.

PREVENTION OF DEADLOCKS IN PACKET-SWITCHED DATA TRANSPORT SYSTEMS
K Gunther
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

This is a useful paper which identifies then describes eight causes of deadlocks in packet-switched networks. The paper goes on to outline the methods which can be used to counteract the deadlock types identified and a general mathematical theory of deadlock prevention is then given.

BUFFER MANAGEMENT IN A PACKET-SWITCH
M Irland
IEEE Transactions on Communications Vol Com 26 No 3 March 1978

This paper considers the performance of a single packet-switch by the use of a queueing model. The model was devised so that the results of previous work on the simulation of CIGALE could be explained. The simulated CIGALE packet-switch employed the concept of a fixed number of shared buffers in which buffer space was allocated on a first come, first served basis. It was observed that unbalanced traffic entering a packet-switch caused the buffers to be allocated to the most demanding link, to the detriment of the less demanding links.

The queueing model is used to show that a restricted sharing of buffers based on link load considerations results in an improvement in congestion control.

A DROP AND THROTTLE FLOW CONTROL POLICY FOR COMPUTER NETWORKS
F Kamoun
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

A congestion control policy based on a so-called distributed drop and throttle flow control scheme is proposed. In outline the scheme relies on each node to differentiate between new and transit traffic. As local node congestion is approached, ie buffer size reaches a predetermined size, new traffic is discarded. If this does not cure the congestion problem, ie the buffers become full, then transit traffic is discarded. A queueing model of the scheme is proposed with symmetrical networks and numerical results for 49 and 121 node networks for various buffer sizes show that the technique is promising for the control of congestion.

ARPANET LESSONS
L Kleinrock
IEEE International Congress on Communications June 1976

This paper emphasises that flow control, an essential feature of packet-switched networks, is an area fraught with hidden problems. Some of the problems experienced with ARPA in the area of flow control are identified and some examples of types of deadlock experience are described.

The conclusion of the paper is that flow control is required which throttles back traffic at source and which guarantees some form of packet ordering detection of duplicates of lost packet recovery. The ARPA experience has shown that these objectives when implemented can lead to unforeseen deadlocks and network performance degradation. The author's advice is that because a flow control protocol cannot be guaranteed degradation and deadlock free, then an implemented flow control scheme must be simplified as far as is possible.

A STUDY OF FLOWS IN AN X25 ENVIRONMENT
J Labetoulle, G Pujolle and N Makou
Flow Control in Computer Networks. IFIP, North Holland Publishing Company (1979)

The queueing model is derived as an aid to the understanding of the behaviour of a network supporting X25 virtual calls. An assessment is made of the effect on flow of varying the two X25 virtual call flow related parameters, window size and packet size. A specific study is made of a 7-node network and the main conclusions are that:

1. Throughput increases only slightly with increasing window size.

2. Ideally window size and packet length should be varied in accordance with the loading on a network, ie as the network load increases, window sizes of new virtual calls should be decreased.

STORE AND FORWARD BUFFER REQUIREMENTS IN A PACKET-SWITCHING NETWORK
S Lam
IEEE Transactions on Communications Vol Com 24 No 4 April 1976

This paper emphasises the difficulty in analysing the buffer requirements in a packet switching network. Reference is made to earlier analytic models which reduce the difficult problem to one that can be solved. However, this reduction process requires certain simplifications to be made such as the assumption of the infinite node storage capacity.

The author proposes a heuristic algorithm for the derivation of buffer sizes based on the assumption that positive acknowledgements must be received from the next node before a packet is deleted, and that packets are discarded on buffer-full conditions.

CONGESTION CONTROL OF STORE AND FORWARD NETWORKS BY INPUT BUFFER LIMITS
S Lam, M Reiser
Proceedings IEEE National Telecommunications Conference (Los Angeles) 1977

This paper investigates by an analytic technique and by simulation a method for the congestion control of store and forward networks by input buffer limits. The input buffer limit technique attempts to control the input rate to the network by discriminating between input and transit traffic at each node and imposing a limit on the fraction of buffers in a buffer pool that input traffic can occupy. The buffer allocation is dynamic in that transit traffic can occupy all the buffers in the pool in times of extreme congestion when input traffic may be denied access.

The conclusion of the work is that the prevention of network congestion is improved, by the use of input buffer limits. However input buffer limits are only one of a number of co-operating methods that should be used for the control of congestion and that they do not guarantee deadlock free operation.

THE RSRE PILOT PACKET-SWITCHED NETWORK
P Masterman
On Line. Data Networks Development and Uses 1980

This paper gives an outline description of the RSRE Pilot Packet-Switched Network and provides background information on requirements of military packet-switched networks. The adaptive routing algorithm employed is mentioned as is the dynamic window method of flow control provided across the switching sub-network.

TRAFFIC MEASUREMENTS IN DATA NETWORKS, RECENT MEASUREMENT RESULTS AND SOME IMPLICATIONS
P Pawlita
IEEE Transactions on Communications Vol Com 29 No 4 April 1981

This paper emphasies that actual traffic measurement is important if reliable estimates of traffic structure and intensity are to be input to packet-switched network models. The general problem of measurement in a distributed network is identified and a proposal for formalisation of a coherent measurement strategy is given. In addition, a review is given of prior work on traffic measurement.

The main conclusions of the paper are:

1. The importance of measurement of network performance is increasing particularly in the area of validation of network models.

2. Measurement systems and techniques need to be improved for both network control centre application and to enable the automatic control of the network.

3. The creation of network independent and standard measurement techniques possibly via the use of the higher layers in the ISO model need to be derived.

4. The measurement of aspects such as dynamic network behaviour and flow control are still in their infancy.

FLOW CONTROL IN DATA NETWORKS METHODS AND TOOLS
L Pouzin
Proceedings International Conference on Computer Communications (Toronto) 1976

This paper is in essence a general discussion document on flow control in data networks. End-to-end flow control, congestion control and traffic dissuading techniques are discussed. One of the conclusions of the paper is that "step-wise" flow control, ie that which can be achieved in virtual channel switching sub-networks, does not present a significant advantage in the distribution of network resources.

A REVIEW OF THE FLOW CONTROL ASPECTS OF NETWORK SIMULATION STUDIES AT THE NATIONAL PHYSICAL LABORATORY
W Price
Flow Control in Computer Networks. IFIP, North Holland Publishing Company (1979)

The author reviews simulation work performed by the National Physical Laboratory over a 10 year period and, where appropriate, comments on the findings of other workers. The simulations were concentrated on networks with datagram switching sub-networks and with specific 10, 18 and hierarchically-structured 50 node topologies.

The general conclusions of the paper, with respect to congestion and flow control, are that:

1. Traffic should be dissuaded at source in preference to being discarded in transit.

2. The management of buffers in nodes impacts on network behaviour and advantage can be taken of this to provide a measure of congestion control.

3. Hierarchically-structured networks pose particularly difficult problems for the implementation of successful congestion and flow control strategies.

METHOD OF DEADLOCK-FREE RESOURCE ALLOCATION AND FLOW CONTROL IN PACKET NETWORKS
E Raubold and J Haenle
Proceedings International Conference on Computer Communications (Toronto) 1976

The proposals in this paper for method of deadlock-free resource allocation and flow control are based on the assumption that channel capacity is the restricting feature of a communications system.

The paper specifically addresses virtual circuit switching sub-networks and proposes that deadlocks can be prevented by structured node buffer pools and that flow control should be arranged by a two-level dynamic window mechanism, ie node-to-node and end-to-end.

The paper concludes that a method of dynamically modifying buffer limits within buffer classes is of interest to the implementation of deadlock free datagram switching sub-networks.

BUFFER SHARING IN COMPUTER COMMUNICATION NETWORK NODES
M Rich and M Schwartz
IEEE Transactions on Communications Vol Com 25 No 9 September 1977

A general queueing model is derived for the analysis of a buffer assignment strategy in which a shared buffer pool is made available for handling overflows from the fixed buffers. The conclusion of the paper is that an improvement in blocking probability is achieved by this approach and that the sensitivity of the systems to variations in traffic is reduced.

ANALYSIS OF CONGESTION CONTROL TECHNIQUES IN COMPUTER COMMUNICATION NETWORKS
S Saad and M Schwartz
Flow Control in Computer Network, IFIP North Holland Publishing Company 1979

This paper provides a summary of some of the various analytic network queueing models which have been derived. Tandem link models appropriate to virtual circuit switching sub-networks and single node in large homogeneous networks, more appropriate to datagram switching sub-networks are described.

INPUT BUFFER LIMITING MECHANISMS FOR CONGESTION CONTROL
S Saad and M Schwartz
IEEE International Conference Proceedings on Communications 1980

This paper extends earlier work on the use of node input buffer limiting for congestion control and the concept of power, the ratio of throughput to delay is used as the performance characteristic to be optimised.

The analysis technique used is one in which attention is focused on a typical node in a large symmetric and homogeneous network.

The use of node input buffer limiting is used to prevent the build up of congestion by limiting the number of buffers available to input packets at all network entry points. Thus transit packets are distinguished from input packets and can be given priority treatment. In addition, selective input link level control is employed when the sum of transit and input packets in a node exceeds a certain level. However, the authors acknowledge that selective input link level control may be difficult to organise.

ANALYSIS OF FLOW CONTROL IN SWITCHED DATA NETWORKS
J Wong and M Unsoy
Information Processing 77. IFIP North Holland Publishing Company (1977)

A general queueing model is derived for the analysis of flow control in packet switched networks. The model is applied to a two level flow control scheme in which level one places a limit on the total number of messages in the network and level two places a limit on the number of messages between source destination node pairs.

The numerical results of the work demonstrate that the method is capable of preventing the network performance from deteriorating when the load generated by one message group is increased.

2.3 ROUTING

Twenty-eight publications are detailed in this section, each one of which concentrates on routing techniques.

A number of different methods of categorising routing techniques are used in the literature and authors have tended to adopt different approaches in the classification of the techniques and this can lead to certain difficulties in reviewing the literature. The main, much

simplified, terms used in this bibliography are:

i. Centralised Routing

Centralised routing employs a network control centre which may have others in standby to increase network reliability. Nodes in the network send information to the control centre relating to traffic intensities and node or link failure. The control centre then computes from time-to-time the network routing strategy and distributes this information to the network nodes.

ii. Adaptive Routing

Adaptive routing implies that routing decisions vary quickly in time on the basis of network topology and traffic flow. Adaptive routing would normally be performed by distributed techniques often by periodic updates between adjacent nodes.

iii. Flooding

In this case packets are broadcast in all or a group of selected directions.

iv. Bifurcation

The splitting of a traffic stream over two routes.

v. Deterministic Routing

Routing is performed according to a predetermined routing sequence derived to give all best network performance under conditions of average traffic intensity.

vi. Hierarchical Routing

A method of organising a large network in a small number of connected regional areas.

2.3.1 Section list of publications

ON DISTRIBUTED COMMUNICATIONS NETWORKS. P Baran. 1964.

ADAPTIVE ROUTING TECHNIQUES FOR DISTRIBUTED COMMUNICATION SYSTEMS. I B Boehm and R Mobley. 1969.

THE TECHNIQUE FOR ADAPTIVE ROUTING IN NETWORKS. R Boorstyn and A Livne. 1981.

A ROUTING PROCEDURE FOR THE TIDAS MESSAGE SWITCHING NETWORK. T Cegrell. 1975.

THE NEED FOR AD/ 'TIVE ROUTING IN THE CHAOTIC AND UNBALANCED TRAFFIC ENVIRONMENT. W Chou, A Bragg and A Nilsson. 1981.

COMPARATIVE EVALUATION OF DETERMINISTIC AND ADAPTIVE ROUTING. W Chou, J D Powell and W A Bragg. 1979.

A HIERARCHICAL ROUTING AND FLOW CONTROL POLICY (HRFC) FOR PACKET-SWITCHED NETWORKS. W Chou and M Shen. 1977.

BASIC DYNAMIC ROUTING PROBLEM AND DIFFUSION. G Foschini and J Salz. 1978.

ADAPTIVE ROUTING TECHNIQUES FOR MESSAGE SWITCHING COMPUTER COMMUNICATION NETWORKS. G Fultz. 1972.

ADAPTIVE ROUTING TECHNIQUES FOR STORE AND FORWARD COMPUTER COMMUNICATION NETWORKS. L Fultz and L Kleinrock. 1971.

DETERMINISTIC AND ADAPTIVE ROUTING POLICIES IN PACKET-SWITCH COMPUTER NETWORKS. M Gerla. 1973.

COMPUTATIONAL CONSIDERATIONS AND ROUTING PROBLEMS FOR LARGE COMPUTER COMMUNICATION NETWORKS. M Gerla, W Chou and H Frank. 1973.

DATA COMMUNICATIONS THROUGH LARGE PACKET-SWITCHING NETWORKS. L Kleinrock and F Kamoun. 1976.

HIERARCHICAL ROUTING FOR LARGE NETWORKS, PERFORMANCE EVALUATION AND OPTIMISATION. L Kleinrock and F Kamoun. 1977.

DESIGN CONSIDERATIONS FOR ROUTING ALGORITHMS IN COMPUTER NETWORKS. J McQuillan. 1974.

ADAPTIVE ROUTING ALGORITHMS FOR DISTRIBUTED COMPUTER NETWORKS. J M McQuillan. 1974.

EFFECTS OF PRIORITY DISCIPLINE IN ROUTING FOR PACKET-SWITCHED NETWORKS. R Pickholtz and C McCoy. 1976.

A STUDY OF BIFURCATED ROUTING IN A DATA NETWORK AND THE EFFECT OF ISARITHMIC FLOW CONTROL IN THIS CONTEXT. W L Price. 1974.

FURTHER SIMULATION EXPERIMENTS ON ADAPTIVE ROUTING USING LOCALLY AVAILABLE PARAMETERS. W L Price. 1975.

ADAPTIVE ROUTING IN STORE AND FORWARD NETWORKS AND THE IMPORTANCE OF LOAD SPLITTING. W Price. 1977.

ARPANET ROUTING ALGORITHM IMPROVEMENTS. E Rosen, J McQuillan, J Herman. 1979.

ON ROUTING AND 'DELTA ROUTING' A TAXONOMY AND PERFORMANCE COMPARISON OF TECHNIQUES OF PACKET-SWITCH NETWORKS. H Rudin. 1976.

THE MODELLING OF ADAPTIVE ROUTING IN DATA COMMUNICATION NETWORKS. A Segall. 1971.

FLOW ADAPTIVE PROCEDURE FOR DYNAMIC ROUTING COMPARATIVE SIMULATION RESULTS. J Selga and J Xampeny. 1980.

ROUTING AND FLOW CONTROL IN TYMNET. L Tynes. 1981.

COMPARISON OF ADAPTIVE ROUTING ALGORITHMS FOR COMPUTER COMMUNICATION NETWORKS. T Yum and M Schwartz. 1978.

THE DESIGN AND ANALYSIS OF A SEMI-DYNAMIC DETERMINISTIC ROUTING RULE. T Yum. 1981.

THE JOIN BIASED QUEUE RULE AND ITS APPLICATION TO ROUTING IN COMPUTER COMMUNICATION NETWORKS. T Yum and M Schwartz. 1981.

ON DISTRIBUTED COMMUNICATIONS NETWORKS
P Baran
IEEE Transactions on Communications Systems, CS-12, March 1964.

This paper is one of a series produced as a result of studies at the RAND Corporation in the early sixties. Comments in the paper on the advantages of adaptive networks in the military environment, in which there is exposure to node and link destruction, are still pertinent.

ADAPTIVE ROUTING TECHNIQUES FOR DISTRIBUTED COMMUNICATION SYSTEMS
I B Boehm and R Mobley
IEEE Transactions on Communications Technology, Vol Com -17, No 3, June 1969.

This paper looks at the problem of routing in a distributed network specifically with the military considerations of performance under damage in mind. A number of techniques are investigated under the flooding and adaptive categories. Network simulation is used to determine the merits of each technique using random node and link destruction. The conclusion of the paper is that the flooding technique is satisfactory only under conditions of low traffic volume and that in all but very small networks, with low traffic utilisation, a technique known as the 'hot potato' method should be used. 'Hot potato' routing is one in which the output queues are ranked and a route is selected on the highest ranked one that is free. Thus, 'hot potato' routing routes messages according to the shortest queue at the decision node with checks to prevent packet circulations.

It should be noted that this is an early paper on the subject and although many of the observations made are still valid a considerable amount of work has been undertaken on routing since that time.

THE TECHNIQUE FOR ADAPTIVE ROUTING IN NETWORKS
R Boorstyn and A Livne
IEEE Transactions on Communications, Vol Com 29, No 4, April 1981

An adaptive routing scheme is proposed for which a simplified analytic model is derived and results for up to 20 node networks demonstrate its improvement over fixed routing under heavy traffic conditions.

The routing scheme is structured in 2 layers:

1. A deterministic routing algorithm based on long-term average flows and network topology.

2. A node adaptive scheme which utilises a dynamic buffer assignment approach for handling transit packets which have alternative routes available.

The way in which such a scheme would be implemented is not fully described. However, the authors propose simulation work to verify their findings.

A ROUTING PROCEDURE FOR THE TIDAS MESSAGE SWITCHING NETWORK
T Cegrell
IEEE Transactions on Communications. Vol Com 23, No 6, June 1975.

TIDAS is a Swedish packet-switched network for the control of an electrical power transmission network. This paper investigates various deterministic and adaptive routing techniques and concludes, on the basis of investigation by simulation, that an adaptive routing technique is the most suitable. In outline, the routing algorithm chosen was adaptive and similar to the ARPA approach, ie of the co-operative update type in which delay tables are held by each node; these being periodically up-dated by information received from adjacent nodes and information on queue lengths local to each node. However, certain extensions to the ARPA approach are proposed such as the addition of event driven local to a node delay table up-dating in addition to periodic adjacent node up-dating.

One of the conclusions of the paper is that the use of local event driven up-dating reduces nodal congestion but with an increase in local processing.

THE NEED FOR ADAPTIVE ROUTING IN THE CHAOTIC AND UNBALANCED TRAFFIC ENVIRONMENT
W Chou, A Bragg and A Nilsson
IEEE Transactions on Communications, Vol Com 29, No 4, April 1981

This is an interesting paper in that it demonstrates, by simulation, that adaptive routing offers advantages in chaotic and unbalanced traffic conditions. Although the paper does not specifically address the advantages of adaptive routing under damage, clearly damage will lead to, at least in the short term, chaotic and unbalanced traffic. The main findings of the paper are worth summarising, and they are:

1. Under statically stable and predictable traffic conditions, well chosen deterministic routing performs better than adaptive routing.

2. Either well chosen adaptive or deterministic routing is appropriate for balanced traffic with surges. Deterministic routing better at high throughputs and adaptive routing at lower throughputs.

3. Well chosen adaptive routing performs better in unbalanced and chaotic traffic environments.

COMPARATIVE EVALUATION OF DETERMINISTIC AND ADAPTIVE ROUTING
W Chou, J D Powell and A W Bragg
Flow Control and Computer Networks, IFIP North Holland Publishing Company (1979).

A simulation model based on ARPANET, in particular its flow and congestion control procedures, is used to compare deterministic and adaptive routing techniques under a variety of conditions. A 10 node network is simulated and various traffic conditions including balanced, balanced with superimposed surges and unbalanced, are applied.

The conclusion of this paper is that deterministic routing provides better network performance except when there are unpredictable surges of traffic or if the network traffic requirements are unknown.

A HIERARCHICAL ROUTING AND FLOW CONTROL POLICY (HRFC) FOR PACKET-SWITCHED NETWORKS
W Chou, M Shen
Computer Performance, North Holland Publishing Company (1977)

The authors put forward the view that the management of traffic flow in a network is complex and involves the intimate relation of routing and flow control. Adaptive routing algorithms used in networks such ARPANET tend to require a large overhead for updating traffic and often only optimise performance locally. This leads the authors to the identification of a hierarchical routing and flow control policy which requires a low updating overhead and performs global performance optimisation which is simulated using a 10 node network with regional supervisory controllers.

The conclusion of the paper is that a hierarchical routing and flow control policy provides better network performance than adaptive routing and should also be easy to implement.

BASIC DYNAMIC ROUTING PROBLEM AND DIFFUSION
G Foschini and J Salz
The IEEE Transactions on Communications, Vol Com -26, No 3, March 1978

This paper highlights that quantative statements as to the performance advantage of adaptive routing, compared with deterministic routing, or determinations of what specific adaptive algorithms are to be preferred, are extremely difficult to make. The underlying reason for this difficulty being the inadequacy of traditional analytic techniques in dealing with networks with state-sensitive dynamics. The paper takes the view that classical queueing approaches are too microscopic in their description and lead to over complex system models, and on the other hand macroscopic models that deal with the transmission of packets as average flows, have not successfully represented the stochastic nature of the input, and do not allow meaningful performance evaluations.

The conclusion of the paper is that the correct model lies somewhere between these two extremes and diffusion is put forward as being a possible model. The approach in diffusion approximation is explained, and is used to determine that an adaptive routing scheme using the vector of queue sizes as the basis of the algorithm routing, has under heavy traffic conditions, an advantage in terms of end-to-end delay time over a deterministic routing scheme.

ADAPTIVE ROUTING TECHNIQUES FOR MESSAGE SWITCHING COMPUTER COMMUNICATIO; NETWORKS
G Fultz
University of California, School of Engineering, Report 7252 1972
Accession No AD/749678

This large report, 409 pages, initially provides a summary of work performed on routing techniques up to 1972 and then gives a comprehensive description and comparison of routing techniques.

The factors that should be taken into account in deciding on a particular routing scheme are discussed, in particular with respect to large networks. A chapter is also devoted to the measurement of network performance and network modelling.

ADAPTIVE ROUTING TECHNIQUES FOR STORE AND FORWARD COMPUTER COMMUNICATIONS NETWORKS
L Fultz and L Kleinrock
IEEE Proceedings. International Conference on Communications June 1971

A classification of routing techniques is given which identifies and briefly describes seven techniques. The techniques identified are flooding, fixed routing, network routing, control centre, ideal observer routing, random routing, isolated routing and adaptive routing. A study of the performance in this paper measured in terms of average single packet message delay of each routing technique is made by simulation and the results compared with measurements taken on ARPANET.

The conclusion of this paper is that fixed routing based on deterministic evaluation offers the best performance with a static network topology and consistent traffic flow. However, adaptive routing provides efficient performance under varying topologies and traffic conditions.

DETERMINISTIC AND ADAPTIVE ROUTING POLICIES IN PACKET-SWITCH COMPUTER NETWORKS
M Gerla
IEEE Proceedings Third Data Communications Symposium 1973

Deterministic and adaptive routing techniques are compared by analytic and simulation techniques and results show that the flow pattern of each technique is similar at low to moderate traffic loads. However, it is pointed out that actual network experience with ARPANET has identified shortcomings with adaptive routing particularly under heavy traffic loads. A centralised routing scheme is proposed as a possible solution.

COMPUTATIONAL CONSIDERATIONS AND ROUTING PROBLEMS FOR LARGE COMPUTER COMMUNICATION NETWORKS
M Gerla, W Chou and H Frank
IEEE National Telecommunications Congress, Atlanta, November 1973

This paper addresses the increased problems of route computation and congestion control in large, ie greater than 100 node, networks. A hierarchical network structure is proposed as a possible method of reducing the route computation. A deterministic and an adaptive routing strategy are assessed in terms of computing requirements for both non-hierarchical and two-level hierarchical structures. It is shown that adaptive routing requires for non-hierarchical structures processing power at each node proportional to the number of nodes, whereas for hierarchical network structures, the computing power required is proportional to the square root of the number of nodes.

The main conclusions of the paper are that hierarchical network structures reduce computational requirements but present new congestion control problems.

DATA COMMUNICATIONS THROUGH LARGE PACKET-SWITCHING NETWORKS
L Kleinrock and F Kamoun
Proceedings. 8th International Teletraffic Congress. Australia.
November 1976

This paper puts forward a view that the design of a non-hierarchically organised network having hundreds of nodes, becomes an impossible task, particularly if adaptive routing is employed, when the size of the routing tables and the sheer amount of network routing data becomes unmanageably large.

An adaptive hierarchical philosophy in which nodes are clustered is proposed and evaluations show that good network performance can be achieved. The advantages of clustering being reduction in the network design and routing problem. However, it should be pointed out that flow control is not specifically covered and that the NPL work on hierarchically-structured networks observed problems in this area.

HIERARCHICAL ROUTING FOR LARGE NETWORKS, PERFORMANCE EVALUATION AND OPTIMISATION
L Kleinrock and F Kamoun
North Holland Publishing Company. Computer Networks 1 (1977)

The authors put forward the view that adaptive routing in networks having large node populations can give rise to problems in storing and updating of node routing tables. One solution to this problem is the hierarchical routing - a method by which nodes are clustered to minimise the size of routing tables. An analytic approach is taken to show that in a very large network the size of routing tables may be reduced with essentially no increase in network path length by the use of hierarchical routing.

DESIGN CONSIDERATIONS FOR ROUTING ALGORITHMS IN COMPUTER NETWORKS
J McQuillan
Proceedings Seventy Hawaii International Conference Systems Science,
Jan 1974

This is a discussion paper which attempts to identify the important issues to be considered when designing routing algorithms. Many of the ideas put forward being based on experiences with the earlier ARPANET adaptive routing algorithm.

ADAPTIVE ROUTING ALGORITHMS FOR DISTRIBUTED COMPUTER NETWORKS
J M McQuillan
Bolt Beranek and Newman Inc. Report BBN-2831. Accession No AD-781467,
May 1974

This large report, 436 pages, is one of the most widely referenced works of the 1970's on adaptive routing algorithms for distributed networks. It provides a comprehensive review of the work performed on adaptive routing prior to 1974. Prior routing classifications by Gerler and Fultz are discussed, and a different classification is proposed in which the method of routing control is the primary factor. The methods of routing control identified are:

1. Deterministic, fixed control at nodes.

2. Isolated independent control at nodes.

3. Distributed equal shared control at nodes.

4. Centralised network control centre.

A number of adaptive routing algorithms for distributed computer networks are described in detail and the issue of routing in large networks by hierarchical methods is discussed.

EFFECTS OF PRIORITY DISCIPLINE IN ROUTING FOR PACKET-SWITCHED NETWORKS
R Pickholtz and C McCoy
IEEE Transactions on Communications, Vol Com 24, No 5, May 1976

This paper addresses the area of the potential improvement in performance of adaptive routing algorithms by the inclusion of fairly minor enhancements and in particular the enhancement study is that of handling packets on a priority basis according to packet age.

The routing algorithms studied by simulation, with 8 and 9 node networks were; fixed minimum hop and two classes of adaptive routing algorithms.

The simulation work not only included variations in offered traffic but also the random destruction of half the network links. It was found that network performance in terms of average delay, throughput and number of undelivered messages could be increased at high network loads or in damage if the algorithms included a priority discard scheme based on packet age.

A STUDY OF BIFURCATED ROUTING IN A DATA NETWORK AND THE EFFECT OF ISARITHMIC FLOW CONTROL IN THIS CONTEXT
W L Price
NPL Report COM 72. March 1974.

A study, by simulation, is made of bifurcated routing for one network topology. In addition simulation runs were performed using the isarithmic method of flow control.

The main conclusion of the paper is that for the particular network topology simulated there was no advantage, in terms of network carrying capacity, in the use of bifurcated routing with isarithmic flow control over a simple fixed routing rule. However the author suggests that for different network topologies a different conclusion could be reached.

FURTHER SIMULATION EXPERIMENTS ON ADAPTIVE ROUTING USING LOCALLY AVAILABLE PARAMETERS
W L Price
NPL Report Com 81. December 1975

The simulation work described in this paper was performed for the comparison of various adaptive routing techniques in their ability to handle surge traffic between single source to destination node pairs.

The main conclusion of the paper is that route bifurcation, in comparison with fixed or overflow routing, can potentially improve network performance under surge conditions between particular source to destination node pairs.

ADAPTIVE ROUTING IN STORE AND FORWARD NETWORKS AND THE IMPORTANCE OF LOAD SPLITTING
W Price
Information Processing 77, IFIP North Holland Publishing Company (1977)

This paper concerns itself particularly with the potential improvement in network performance, by arranging more even traffic distribution, if adaptive routing algorithms have the ability to perform bifurcation. The results of simulating a 10 node network comparing an adaptive routing algorithm with and without load splitting features with high network laodings demonstrated that bifurcation offered an improvement in performance. However, this advantage is to a certain extent offset by the additional processing required for packet re-ordering.

ARPANET ROUTING ALGORITHM IMPROVEMENTS
E Rosen, J McQuillan, J Herman
Bolt Beranek and Newman Inc. Report BBN-4088 Accession No ADA086340 1979

This report, one of a series on ARPANET routing algorithm improvements, contains some useful chapters on network testing to demonstrate the efficacy of the new routing algorithm. Also, enhancement to congestion control by possible improvements to node buffer management is described.

ON ROUTING AND 'DELTA ROUTING' A TAXONOMY AND PERFORMANCE COMPARISON OF TECHNIQUES OF PACKET-SWITCH NETWORKS
H Rudin
IEEE Transactions on Communications, Vol Com 24, No 1, Jan 1976

The author puts forward the concept of delta routing which in essence is a combination of adaptive and deterministic techniques. The rationale behind the technique proposed is that the adaptive element of the algorithm controls instantaneous local traffic flow and that this is supplemented by a global view of the network provided by the centralised deterministic part of the algorithm.

The classification of routing algorithms is given together with an overview of several alternative strategies. The results of comparing a number of adaptive and deterministic algorithms with delta routing by simulation of a four and a ten node network are given in terms of delay and trunk carrying capacity.

The author concludes that delta routing offers a potential improvement in network performance, but recognises that the actual measure of network performance for comparison purposes represents a difficult problem area.

THE MODELLING OF ADAPTIVE ROUTING IN DATA COMMUNICATION NETWORKS
A Segall
IEEE Transactions on Communications, Vol Com 25, No 1, January 1971

The author introduces analytic techniques for the modelling of adaptive routing. The techniques described are not based on queueing theory, but rather on an algorithmic approach which enables a simplification of the problem. The technique is applied to dynamic and so-called "quasi-static" routing and a simple example is given.

FLOW ADAPTIVE PROCEDURE FOR DYNAMIC ROUTING COMPARATIVE SIMULATION RESULTS
J Selga and J Xampeny
IEEE International Conference Proceedings on Communications, 1980

Adaptive routing procedures for ARPA and TIDAS are compared by simulation with a so-called flow adaptive procedure in which a small level of routing information is exchanged between adjacent nodes on the packet flow path for each transmitted data packet. ARPA and TIDAS use a periodic update adaptive routing procedure, with an update period of 10 seconds in the case of TIDAS, 0.66 seconds in the case of ARPA.

The results of simulation of two network topologies with different traffic pattens provides results which suggest that because the flow adaptive procedure encourages bifurcation, average delay performance, and reaction to damage and congestion handling is improved over the periodic update approach. However, if the periodic update interval of ARPA and TIDAS was reduced by a factor of 10, then similar performance could possibly be achieved but at the expense of 10 times more routing control traffic.

One of the conclusions of the paper is that a hybrid routing scheme employing both periodic updating and flow adaptive procedure may provide an adaptable approach capable of fast reaction to congestion.

ROUTING AND FLOW CONTROL IN TYMNET
L Tynes
IEEE Transactions on Communications, Vol Com 29, April 1981

The author provides an overview of the congestion control strategy adopted by TYMNET 2. TYMNET 2 employs a virtual circuit switching sub-network with routes being selected at call set-up time on a deterministic basis using a mixture of distributed and centralised control. Links between adjacent nodes are called virtual channels and on any one virtual channel a number of virtual circutis may be multiplexed. Flow control is performed in a step-wise fashion on each virtual channel, the onset of congestion being propagated back to source to throttle back new offered traffic. Network failure is automatically catered for and sufficient user data is stored at access nodes to permit the use of transparent handling of failure conditions.

The author observes that no deadlocks have occurred with TYMNET and that it is doubted whether adaptive approaches to routing as employed in some datagram sub-networks would not function as efficiently with large node populations such as are accommodated for in TYMNET. One of the primary reasons for this being adaptive routing which can tend to spread congestion rather than maintaining it as a localised feature.

COMPARISON OF ADAPTIVE ROUTING ALGORITHMS FOR COMPUTER COMMUNICATION NETWORKS
T Yum and M Schwartz
Proceedings National Telecommunications Congress. December 1978

This paper gives the results of analysis and simulation to determine the effects of superimposing adaptive routing rules on fixed rules. The two fixed rules are shortest path and minimum message delay with bifurcation. The two adaptive rules were local queueing information and updating from adjacent nodes.

The conclusion of the paper is that for 3 and 4 node networks with different traffic characteristics, in general, the addition of an adaptive element to a routing algorithm produces a reduction in message delay.

THE DESIGN AND ANALYSIS OF A SEMI-DYNAMIC DETERMINISTIC ROUTING RULE
T Yum
IEEE Transactions on Communications, Vol Com 29, No 4, April 1981

This paper identifies four basic components of network information that can be used for routing decisions as:

1. Topological information.

2. Traffic rate information.

3. Local queue length information.

4. Feed-back information. (This includes the state of the queues and other local information at neighbouring nodes.)

The following two routing algorithms are compared by queueing analysis:

1. An adaptive algorithm which bifurcates traffic, ie splits traffic streams over different outgoing links.

2. A semi-dynamic deterministic algorithm which, under the supervision of a network control centre, also bifurcates traffic.

The paper concludes, that on the basis of the analytic results, the deterministic rule always gives a lower delay performance than the adaptive technique.

THE JOIN BIASED QUEUE RULE AND ITS APPLICATION TO ROUTING IN COMPUTER COMMUNICATIONS NETWORKS
T Yum and M Schwartz
IEEE Transactions on Communications Vol Com 29, No 4 April 1981

This paper investigates by queueing analysis a routing algorithm which comprises an adaptive routing rule overlaying a fixed routing rule. The adaptive rule is of the join biased queue type which can be adjusted for varying degrees of traffic bifurcation.

Some of the unsolved problems associated with the proposed algorithm are discussed and the authors caution that the consideration of any one congestion control mechanism such as routing in isolation from the other mechanisms, may lead to an invalid conclusion.

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